CONF-790810--1

LA-UR-79-1230

TITLE: HEAT TRANSFER AND THERMAL LOSSES IN ABOVE-CORE REGIONS

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SUBMITTED TO: 2nd International Seminar on Containment of Fast Breeder Reactors
International Congress Center
Berlin, (West) Germany
August 9-10, 1979

MASTER

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CONTRACT W-7405-ENG. 36

HEAT TRANSFER AND THERMAL LOSSES IN ABOVE-CORE REGIONS

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SUMMARY

Heat transfer and thermal losses in above-core regions can substantially influence the conversion of thermal energy to damage potential following postulated core-disruptive accidents in a liquid metal fast breeder reactor. Any assessment of these influences is complex and difficult to substantiate because of the transient, interactive environment in which they occur. This paper develops a perspective for the role of heat-transfer processes in the context of fluid/structure dynamics, containment strength, accident severity, sodium involvement, and uncertainties in current knowledge. The Clinch River Breeder Reactor (CRBR) is used as an example to quantify this perspective. Containment limits are estimated for CRBR to allow a comparative evaluation of the containment tolerance as different physical effects are considered. For a conservative estimate of containment failure threshold and for neutronic excursions resulting in fuel-vapor expansions, the CRBR system tolerence for energetic accidents increases if we include the effects of fluid-structure dynamics and coupled fluid-dynamics and heat transfer. Further, additional accommodation for greater sodium involvement (work-potential augmentation) is possible if all heat-transfer processes are considered together. This perspective can contribute valuable insight as decisions are made to reduce the uncertainty in the risk to the public by means of improved analysis of the energetics problem.

*Work performed under the auspices of the United States Department of Energy.

1. Introduction

Containment integrity in postulated fast reactor accidents has been a major area of study for many years. It was recognized at an early point [1] that fast reactors are not in their most reactive configuration; therefore, the historic approach has been to establish criteria [2,3] to prevent potentially serious configurational changes through proper design and fabrication (by using core clamping, highly reliable control rods, high-quality materials, qualified manufacturing techniques, etc.). However, mankind is not infallible and our best expertise and intentions do not produce absolute safety. Therefore, we attempt to prevent serious accidents, to recognize and quantify the uncertainties in our safety systems, to understand the progression and consequences of a variety of accidents (should they occur), and to provide a reasonable level of system tolerance for these unexpected events.

The nature of core disruptive accidents (CDAs) and the manner in which these accidents potentially lead to health consequences are discussed by Marchaterre [4], Theofanous [5], Jackson [6], and others [7,8]. Accident severity (generally stated in terms of reactivity insertion rate at prompt-critical) and the probability of occurrence are dealt with in the literature [9-12]. Our consideration involves the determination of damage potential and quantified threats to the overall containment system (Primary Heat Transport System, PHTS, plus the Reactor Containment Building, RCB) and, in particular, the effects of heat transfer and thermal losses in the above-core regions.

2. Perspective

The translation of the reactivity insertion rate into a thermodynamic initial condition for the so-called postdisassembly expansion occurs in the "disassembly phase" of the accident. This phase generally terminates the neutronic transient in the accident (except for possible recriticality events during the later stages). An overview is given by Jackson [13] of the treatment of the disassembly phase.

The fission energy deposited as thermal energy in the core materials can produce a quantity of work as the materials expand to fill the cover-gas volume between the sodium pool and the reactor head. A thermodynamic work potential can be defined based on an isentropic expansion of the high-temperature fuel alone [14] or a higher theoretical work potential can be defined by recognizing the possible role of the more volatile sodium [15] 1000-MWe.

For reactors in the 1000-MWe class, the problems of accommodating the work potential of CDAs are more critical [16]. Thus it is prudent to take advantage of the nonideal aspects of the expansion process and thereby claias much of the real system tolerance for energetic accidents as can be defensively shown.

Figure 1 qualitatively presents the impact of various nonideal processes during the expansion and reflects design uncertainties and possible design options on system tolerance for CDAs in the Clinch River Breeder Reactor (CRBR) [17], shown schematically in Fig. 2. The figure is primarily illustrative in nature. Most of the quantitative information can be traced to specific detailed calculations. However, the intent is more to show relative trends and the overall tradeoffs involved than to prescribe specific CRBR failure limits.

The thermodynamic work potential shown on the abscissa can be considered either the result of an isentropic fuel vapor or a Hicks-Menzies [15] sodium vapor expansion. The reactivity insertion rates that relate to the thermodynamic work potentials for the cases examined are shown at the top of the figure. Transfer lines between the two scales (line a-b for example) indicate constant reactivity insertion rate as a function of increasing sodium involvement in the expansion. Sodium involvement is defined as the percentage of the optimum Hicks-Menzies work potential that can be produced.

The ordinate of Fig. 1 is pool kinetic energy at impact with the reactor closure system and can be interpreted loosely as damage potential. This kinetic energy may not necessarily correspond to real damage because the impact dynamics will strongly influence the transient forces developed in the system.

For CRBR, a range may be estimated for impact kinetic energies leading to early PHTS and RCB failure. The lower limit is conservative and may be associated with ideal sodium-fire pressurization of the RCB caused by sodium discharge through the reactor head and with "free body" missile generation. There is also a damage-potential level at which the containment system will fail with higher certainty. We have estimated this level to be about 400 MJ (expansion to the cover-gas volume) for the CRBR based on impact pressures at or above one-half the yield strength of the reactor head material. This level is uncertain, but is selected primarily for the sake of evaluating whether the importance of the different physical processes changes when considered at two significantly different containment capabilities (150 MJ vs 400 MJ). The width and position of the failure threshold range shown in Fig. 1 is system design dependent and is a function of head failure modes (e.g., missile generation) and of sodium ejection paths. In addition, the range can be affected through improved understanding of sodium burning, RCB pressurization, and RCB failure characteristics.

The "ideal" conversion process is shown as line A on Fig. 1. Point c is the conservative estimate of system tolerance for energetic CDAs. The figure shows that the system could withstand an accident ramp rate of 60$/s involving only fuel vapor and considerably less with significant sodium augmentation. In moving from point c to d on curve A, we assume that neither sodium fires nor missiles such as ejected rotating plugs cause secondary containment failure over this range of energetics. The maximum potential in system tolerance would be about 120 $/s if we are constrained to curve A and a pure fuel-vapor expansion.

If we exclude the above-core structures (upper-core structure, UCS, and upper internal structure, UIS) and consider only effects of fluid dynamics and fluid/structure dynamics, we shift to zone B on Fig. 1. These expansions are characterized by two-dimensional pool dynamics, loss of work potential through plastic strain of the core barrel and vessel walls, incomplete conversion of pool kinetic energy to loads on the vessel closure system because of incoherent pool impact, and incomplete development of work potential because of the nonuniformity in the dynamic expansion. These effects are fairly well understood and can be calculated to various degrees with computer codes such as REXCO [18], SIMMER [19], ICECO [20], PISCES [21], ASTARTE [22], and SURBOUM [23]. Considerable experimental data has been accumulated in support of these fluid/structure effects [24-27] and more is being obtained on the nonuniform expansion behavior [28]. The bandwidth shown for region B arises from a ± 20% assumed uncertainty around a nominal estimate.

As seen from Fig. 1, these effects reduce the conversion efficiency to about 50 per cent of the ideal. This shifts the lower limit of system tolerance from 60 $/s (point c) to a range of 90 to 125 $/s. Of more importance is the potential for extending system tolerance to around 240 $/s if sodium fire and missile threats can be accommodated. The likelihood for severe fires and energetic missiles clearly increases as the reactivity ramp rate increases, however.

Work potential is diminished by heat losses from the working fluid. The heat-transfer processes are coupled strongly to the structural behavior of the fluid dynamics and to the high heat capacity of the fast-response UCS. The combined effects of all the heat-transfer processes (assuming the UCS and UIS remain in place and unplugged) are estimated [29] as region C in Fig. 1. It must be emphasized that region C represents not only heat-transfer effects, but the combined result of severe fluid throttling in the UCS pin structure and heat transfer in the core, UCS, and sodium pool. (See Sec. 3 for details of these processes.)

Region C cannot be accepted in the high work-potential regime because the UCS and UIS are likely to fail dynamically under the higher core pressures. Recent experimental work at SRI [30] shows large UIS translations for simulated isentropic fuel-vapor expansions in the range of 200 MJ (to the cover-gas volume). Because these were direct-loading experiments (i.e., there was no UCS between the core and UIS) and the flow passages of the UIS were blocked, the deformations of the columns are probably somewhat large compared to the real case. The effectiveness of the UCS could begin to deteriorate at approximately 150 $/s. The work potential has not yet been determined at which the mitigating effects of the UCS essentially disappear but we estimate that the pins in the UCS probably would begin to buckle and flow passages would jam at approximately 200 $/s. UCS effectiveness as a heat sink would depend on the degree of interpenetration of core material before and during this mechanical jamming.

An estimated UCS breakdown zone is shown on Fig. 1 as region D. Some effect of thermal losses continues even in the work-potential range beyond complete UCS breakdown because of heat-transfer processes at the expansion zone/pool interface. Heat-transfer processes in the core also will remain to some degree. Thus the CRBR system tolerance for energetic accidents may be extended to the range of 150 to 200 $/s if fuel is the expanding fluid, a conservative containment-failure threshold is used, and if heat transfer and above-core structure effects are included.

Figure 3 presents a summary of the CRBR system tolerance for energetic accidents in terms of reactivity ramp rate vs the expansion treatment used. The lower-case letters that designate various ranges are preserved from Fig. 1. The left-hand band (cehigc) represents the conservative limit of containment-system tolerance and the band width represents an estimate of uncertainties. The magnitudes of the uncertainties may be questioned but the qualitative trends are valid. The right-hand band (djkℓfd) represents an upper limit of containment through increased understanding of the failure threshold and perhaps implementation of special design features to elevate the threshold.

Opposite curvature of the two bands is one feature of Fig. 3 that is very prominent and has an important impact on the need to understand heat transfer and thermal losses in the above-core structure. The left-hand (conservative) band indicates a substantial gain in system tolerance if the heat-transfer processes are assessed and substantiated. The right-hand (optimistic) band indicates marginal value for heat-transfer effects in the high ramp-rate regime. This is mainly the result of the threshold nature of the UIS failure. In addition, the high ramp-rate expansions allow less time for heat transfer, thereby diminishing that influence.

A second prominent feature of Fig. 3 is the inverse dependence of containment-system tolerance on the degree of sodium involvement. Containment of even a mild accident requires low levels of sodium involvement. It is this characteristic of the liquid fuel-steel-sodium system that has provided the impetus for many years of research on an international scale in the area of fuel-coolant interactions (FCIs).

A containment failure regime map that depends on reactivity ramp rate and effective sodium involvement is shown in Fig. 4 for the three sets of modeling assumptions that form the bases for regions A, B, and C in Fig. 1, i.e., an ideal expansion, an expansion considering fluid dynamic and structure effects only and an expansion including both heat transfer and fluid dynamics effects. This failure map was derived from Fig. 3 using points c,e, and h as the containment-failure thresholds for the three expansion treatments. For mild accidents (< 50 \$/s) heat transfer may substantially relax the requirement that we must demonstrate small effective sodium involvement. Heat transfer would also permit substantial sodium involvement in the intermediate ramp-rate range (50-150 \$/s). In the higher ramp-rate range (> 150 \$/s), augmentation from sodium involvement can be tolerated only if uncertainties in UCS and UIS breakdown characteristics are resolved, the containment-system failure threshold is increased, and/or specific design changes are made to shift the positions of regions B and D downward and to the right in Fig. 1.

3. Heat Transfer Processes

3.1 Heat Transfer in the Core

The fundamental consideration relative to heat transfer is timing. Any heat-transfer process that can rapidly remove a significant portion of the sensible energy that was added to the fuel during the disassembly phase may have either the effect of significantly lessening or augmenting accident severity. Therefore those heat-transfer processes that are operative with high-exchange rates are of importance to us here.

Following the disassembly phase, the core is in a state where fuel is at a high temperature relative to the remaining steel and sodium (liquid steel, solid cladding, solid can wall, liquid sodium, or various combinations depending on the accident sequence). In addition to the fuel-steel and fuel-sodium paths for energy loss from the fuel, the spatial power distribution significantly varies the fuel temperatures throughout the core. Thus, energy can transfer from hot to lower-temperature fuel through intermixing.

Abramson [31] performed a parametric study of the effects on the work potential of heat transfer between in-core liquid fuel to liquid steel. This process was found to decrease the work potential by as much as an order of magnitude. The magnitude of the effect decreases with higher initial steel temperature and with less available steel mass for energy absorption. Of critical importance also is the characteristic size of the steel and the strength of the thermal coupling. This heat-transfer mode should be of major importance in most accidents because the steel is initially in a highly distributed state (cladding thickness of $\sim$ 0.0004 m, can-wall thickness of $\sim$ 0.003 m, and steel droplets on the order of the flow-channel hydraulic diameter, i.e, $\sim$ 0.003 m) and because the fluid behavior is highly transient initially (in-core velocites on the order of 100 m/s) thereby generating strong thermal coupling.

The effect of fuel-steel heat transfer also has been calculated with SIMMER-II, which analyzes all the coupled heat transfer/fluid dynamics effects interactively. The early, highly transient fluid behavior calculated by Abramson was reproduced also. We found that the core pressure decreased very rapidly because of the preferential expansion of high-temperature core material at the core center. As a result, the core material was driven to the core boundaries.

This rapid redistribution of material not only enhances contact between liquid fuel and steel but also promotes a process called "self-mixing." The term refers to the self-driven expansion of hot fuel into colder fuel with associated thermal equilibration. If this process is sufficiently strong, the available work potential can be reduced by a factor of two in the early phase of the expansion. With strong self-mixing, the core expansion is characterized by the initial mean fuel temperature instead of the peak fuel temperature; however, this degree of self-mixing has not yet been verified experimentally.

If severe neutronic excursions occur with a large fraction of the core containing sodium, the distributed arrangement of fuel and sodium in the core suggests that a high percentage of the Hicks-Menzies work potential might develop. The criterion for large-scale initial coarse mixing appears to be satisfied [32], a substantial inertial constraint exists, and the opportunity for massive heat transfer is present even if not on a vapor-explosion time scale. Fauske [33] has pointed out that sodium in the core requires the presence of relatively cold cladding and subassembly can walls. Because the cladding is initially a barrier between the liquid fuel and sodium, it should impede the mixing of the two materials, at least at low ramp-rate levels.

In addition to impairing mixing, the cladding material can degrade work potential through heat absorption. Heat transfer to the cladding reduces the available work potential by an amount approximately equal to 5 per cent (Hicks-Menzies efficiency is about 5% for expansions to the CRBR cover-gas volume) of the thermal energy lost from the sodium. If all the cladding in the active core of the CRBR were heated from about 800 K to the melting point by the fuel/sodium mixture, a work-potential reduction of about 50 MJ would result. The reduction is relatively small because the dependence of work potential on fuel temperature for Hicks-Menzies expansions is much weaker than for fuel-vapor expansions. Cladding will be of major influence in situations where the effective mixing is limited to a small fraction of the active core length. Then the 50-MJ effect of the cladding becomes a significant fraction of the available work potential.

The role of in-core heat transfer on loads delivered to the above-core structures is also extremely important. Because of the strong dependence of fuel-vapor pressure on fuel temperature, processes that rapidly reduce fuel temperature will strongly affect the structural dynamics of the pins in the UCS and the overall movement of the UIS. Under some circumstances, heat transfer from an in-core FCI mixture will also affect the forces on the UCS and UIS. Figure 5 presents a qualitative summary of the influence of in-core heat-transfer processes on above-core structure-loading transients. The solid curve is a SIMMER-II calculation of the spatially integrated force applied to the UCS for a CRBR isentropic fuel-vapor expansion. The initial conditions for this calculation were a completely voided core and UCS, an average fuel temperature of 4800 K, a peak fuel temperature of 6000 K, and molten subassembly can walls. The force is small initially because of the low fuel-vapor pressure at the top of the core. The dynamic character of the force is a result of the bulk motion of the core material as it responds to the initial fuel-vapor pressure gradients of $\sim$ 50 MPa/m. The maximum force is a factor of three below that which would occur if the peak fuel-vapor pressure were applied over the entire core cross-sectional area. Thus the actual UCS loading during a simulated isentropic expansion is not as severe as that obtained from purely thermodynamic considerations or that applied in the UIS dynamics tests at SRI [30].

If the self-mixing process is very rapid, the core pressure drops quickly over the entire core area to about 3 MPa for the 4800-K initial condition, thereby producing a force on the UCS of about 8 MN. This force as well as those discussed below is shown as a level on Fig. 5. There is no implication that these forces persist over the time scale of the abscissa. The forces would, in reality, decrease with time. Consequently, the effect of self-mixing on the UCS loading can be at most an additional reduction of about a factor of three compared to the SIMMER result.

Heat transfer from liquid fuel to steel also can have a significant effect on the loading of the UCS. This process should be assessed in a dynamic manner because of the steel vapor produced if rapid heat transfer occurs to a small quantity of participating steel. In fact, there should be a mixture ratio for fuel and steel at which the ability to damage and displace the UCS and UIS is maximized in the same way as the Hicks-Menzies work potential is maximized for fuel/sodium mixtures. This aspect should be considered further to determine whether steel can amplify the UCS loading in voided-core accidents. To assess the influence of fuel-steel heat transfer on the upward-directed force, we assumed that all of the cladding is available in a dispersed form for rapid equilibration with the fuel. The result is a mean mixture temperature of about 3700 K. A steel-vapor pressure of about 1 MPa is produced that delivers a force of about 3 MN to the UCS (as shown on Fig. 5).

Finally, we must consider the sodium-in-core situations where sodium vapor becomes the pressurizing fluid. As we indicated in Sec. 3.1, the early mixing characteristics are of primary importance. The influence of rapid heat transfer to cladding plays an important role only if the mixing mechanics limit the scale of the work potential. The same is true for the forces applied to the above-core structures. To determine the effect of heat transfer from the FCI mixture (assuming no thermal decoupling of fuel and sodium in the early part of the expansion) to the intact cladding, we looked at equilibration conditions for different postulated FCI levels in the core. If 10 per cent of the core volume suffers a Hicks-Menzies event and all the cladding in the core is available as a fast-acting heat sink, the equilibration temperature becomes 1630 K, producing a force of 6 MN on the UCS. A 20-per cent core FCI produces a force of 36 MN. These levels are plotted on Fig. 5 for comparison. A 100-per cent FCI produces supercritical sodium even with rapid heat transfer to cladding, resulting in forces on the order of 300 MN. We estimate the force level required to rapidly eject the UCS as a result of large UIS deformation to be of the order of 100 MN.

3.2 Heat Transfer in the Upper-Core Structure

UCS cladding is particularly important in the postdisassembly expansion phase of both voided-core and sodium-in-core accidents. The heat-transfer processes in the UCS occur in a more ordered structural environment, are highly transient and interactive, and control to a large extent the nature and quantity of the material ejected into the sodium pool. The cladding generally will be heated beyond its melting point. This introduces a dynamic character to the flow channels and therefore a strong feedback on the fluid dynamics. The heat transfer also leads to phase and composition changes in the fluid flowing through the UCS. Finally, the situation can become even more complicated if large structural deformations occur in the pins of the UCS because of the imposed fluid-dynamic and thermal loads.

Because UCS heat-transfer processes are complex, the temptation is strong to translate the total heat-sink capacity of the UCS into an available reduction in work potential independent of heat-transfer details. By doing this, we find that for the CRBR the total cladding in the upper-axial blanket and fission-gas plenum regions can absorb about 1400 MJ in heating from 1200 K to the melting point for a voided-core accident and about 1500 MJ in heating from 800 K to the melting point for a sodium-in-core accident. By converting these decreases in available energy to decreases in work potential for an isentropic fuel-vapor expansion and a Hicks-Menzies expansion to the CRBR cover-gas volume, we can attain reductions in work potentials of about 100 MJ and 150 MJ respectively. At low-accident severities these reductions are indeed significant. However, as the severity increases to levels greater than 500 MJ, the effect of UCS heat transfer would be minimal from this type of integral assessment.

To ascertain the complete UCS effects on postdisassembly expansion, we must examine the detailed processes in an interactive manner. In 1977, we used SIMMER-I [34] to analyze the fuel-vapor expansion with a multifield, multicomponent fluid-dynamics model coupled with multipath heat transfer including phase changes. The various exchange processes for mass, momentum, and energy were modeled simplistically, but the correct global dependencies were preserved. In this early analysis [29] we quantified the large throttling character of the UCS and also the <u>net</u> reduction in system kinetic energy as a result of all heat-transfer processes. (In these calculations, the working fluid in the region above the UCS changes from fuel to sodium.) The UCS removes most of the fuel vapor from the two-phase fluid leaving the core and produces a multicomponent stream of liquid fuel and liquid steel at the exit of the UCS. These liquids subsequently interact with the liquid sodium in the pool to produce sodium vapor that drives the expansion. Thus the damage potential results from the interplay between mitigating heat-transfer effects in the core and UCS and augmenting heat-transfer effects in the pool.

In the SIMMER calculations, a low-void fraction, two-phase mixture of liquid fuel and liquid steel initially is forced into the upper axial-blanket region as a result of the rapid redistribution of core materials to the core boundaries. The high-temperature mixture flashes as it encounters the low-pressure environment of the UCS. This process rapidly disperses the liquid. Thus, in the early phase of UCS interaction, there is heat transfer between liquid fuel and liquid steel in the flow channels, liquid fuel and cladding, liquid steel and cladding, fuel vapor and cladding (condensation on cladding) in the dispersed flow regions, liquid fuel and fuel vapor (vaporization and condensation), liquid steel and fuel vapor, and cladding and upper axial-blanket fuel. In addition, cladding ablates in this environment thereby increasing the hydraulic diameter while adding liquid steel to the fluid stream and enhancing fuel-to-steel heat transfer. Heat transfer with sodium may also occur depending on the initial sodium distribution in the UCS. Because the interaction of core material with sodium in the UCS involves a spray-type mixing in small channels with local void space, the pressure generation is rather mild and momentary. The sodium vapor generated in this small-channel environment expells the remaining sodium out of the UCS.

As the expansion continues to drive material through the UCS and the full length of the UCS is engaged by the flowing fuel/steel mixture, the UCS strongly restrains high-velocity, high-density flow. The result is a limited-mass throughput of material from the core to the sodium pool above. This throttling process has a strong compounding effect on all heat-transfer processes. It lengthens the time of expansion so that mitigating heat-transfer processes in the core have longer to reduce the driving pressure that ejects material through the UCS. The low throughput of material in the UCS produces incoherent and incomplete mixing with the sodium above the UCS. The slow sodium vapor-generation rate in turn enhances the mitigating heat-transfer processes in the pool.

Eventually the UCS pin structure is completely ablated, thus losing its throttling capability. At this point the core pressure is substantially reduced as a result of expansion, self-mixing, and heat transfer to in-core steel. Further, the bulk sodium interface is now a few meters from the hot core material, thereby effectively preventing highly coherent and rapid mixing with sodium.

The UCS and associated heat-transfer processes do far more than simply absorb sensible energy from the working fluid. The induced effects on the total integrated expansion are the dominant mitigating features in the intermediate accident-severity range. This total influence can be assessed only by considering the interactive details of the expansion. Many complexities are involved; however, through the use of new tools, such as SIMMER-II [19], sensitivity studies that scope the effects of modeling inadequacies and data base uncertainties [35], and experimental efforts such as those at Purdue [28], Los Alamos Scientific Laboratory [36], and Argonne National Laboratory [37], we may gain sufficient understanding and confidence to take advantage of the complete UCS influence on the generation of damage potential.

UCS heat transfer when sodium is the working fluid is important [38] and also may be substantially larger than expected from heat-sink considerations alone. We have performed several SIMMER-II calculations with sodium initially in the core region. Strong heat-transfer coupling between the liquid fuel and sodium was applied and the mixing of the fuel and sodium was instantaneous over the portions of the core containing sodium. The Hicks-Menzies work potential for the selected initial conditions was about 700 MJ for expansion to the CRBR cover-gas volume. Of particular interest is the comparison of results between two CRBR cases, one with UCS and UIS in place and one with neither in place. The maximum system kinetic energies were about 15 MJ and 150 MJ respectively.

The thermal/fluid dynamics aspect of the expansion accounts for at least one-half the reduction in damage potential for the no-structure case. The expansion deviates in two important ways from the ideal. First the thermal equilibrium is not maintained between the fuel and sodium during the expansion. Padilla [39] indicates that this feature alone can lead to about a factor-of-two reduction in the delivered work to the system. Second, the working fluid does not expand uniformly during the approximately 30-ms expansion period. Therefore, all portions of the working fluid do not develop work potential to the same degree. This effect has been investigated [40] and was found to represent a 30 to 50 per cent reduction in the work delivered by the working fluid.

As in the fuel-vapor expansion, the resistive character of the UCS not only prevents the in-core FCI pressure from acting directly on the sodium pool, but it enhances the in-core heat transfer between the sodium/fuel mixture and the in-core steel, the heat transfer between the expelled mixture and the cladding in the lower part of the UCS, the effect of condensation in the sodium pool, and self-mixing of sodium in the pool - all as a result of the lengthened time for expansion. Much of the cladding in the core and the lower part of the UCS is heated well beyond the steel melting point (to a range of 2200 K) before the upper part of the UCS is destroyed by the heating process. Thus the effectiveness of the cladding as a heat sink is increased by at least a factor of two over that which was postulated from global heat-sink considerations. Of perhaps more importance is the promotion of greater heat transfer in the pool. This is evidenced by the continual decrease in the mass of sodium vapor in the SIMMER-II calculation even though energy is continually transferred to the sodium by the fuel and steel during the expansion.

3.3 Heat Transfer in the Sodium Pool

Heat transfer in the sodium pool is important both with and without the above-core structures. The major pool heat-transfer processes are condensation, self-mixing, vapor to liquid sodium, liquid and particulate fuel to sodium, and liquid steel to sodium.

The condensation and vapor heat-transfer processes are particularly dependent on the interfacial area between the pool and expansion region. Therefore, these processes are very sensitive to liquid sodium entrainment during the expansion. The degree of entrainment in particular designs and particular expansions cannot be determined with confidence at this time.

These interfacial processes may reduce the pressure locally at the pool interface, thereby reducing the effective acceleration of the pool [41] or may increase the local pressure if hot vapor is involved [42].

The other heat-transfer processes involve mixing of hot material from the core region with the sodium of the pool. Fuel-vapor expansions with an intact UCS tend to produce jets of two-phase fuel and steel at the exits of the subassemblies. These jets cause forced mixing of core material and sodium at least in the early part of the expansion when the sodium interface is near. The integral extent of the energy transfer is a function not only of the mixing details but also of the fluid-dynamic response of the jets and the pool to the buildup of sodium vapor backpressure. This type of mixing generally continues along with the associated heat transfer until sufficient backpressure is developed to move the sodium interface away from the mixing region. If the jet material is fuel and steel, the mixing augments the generation of pool kinetic energy. If the jet material is a high-temperature mixture of fuel and sodium, however, the mixing mitigates the generation of pool kinetic energy.

Some concern exists regarding the forced mixing of fuel/steel jets with sodium in the early part of the expansion. It is associated with postulated, delayed thermal interactions where large accumulated quantities of liquid fuel and steel could potentially interact in a coherent manner. The result would be an increase in damage potential. Simulation tests such as those planned at Purdue [28] using a more volatile fluid for the pool than for the simulated core material will provide us with more data in this regard. Large integral tests with actual reactor materials may be needed if the combined mixing mechanics and thermal interactions in this type of environment cannot be understood sufficiently and substantiated with out-of-pile and small-scale experiments.

4. Conclusions

Energetic expansions of high-temperature materials following postulated severe neutronic excursions in LMFBRs are complex, highly transient, and highly interactive. In addition, the assessment of containment-system failure thresholds is difficult and complex. Therefore, these many facets of the problem should be integrated to allow consistent cost-benefit decisions to be made regarding research and development needs, safety-related design features that increase system tolerance for energetic events, and approaches to formulating a defendable safety assessment. We have attempted to provide a perspective of this type for the CRBR. This can be translated partially to other designs but the estimated containment limits and the translations of ramp rates to work potentials may be different.

Heat-transfer processes in general are important, as are the combined thermal/fluid dynamics processes associated with the above-core structure. The role of heat transfer and UCS interaction should be considered and integrated into safety assessments to obtain realistic system tolerances particularly for sodium-in-core CDAs. This discussion suggests that the details of the expansions are important in assessing these thermal/fluid dynamics effects. It is only through an understanding of these macroscopic details that the full impact of the heat-transfer processes can be realized in assessing the estimated tolerance of containment systems for energetic LMFBR accidents.

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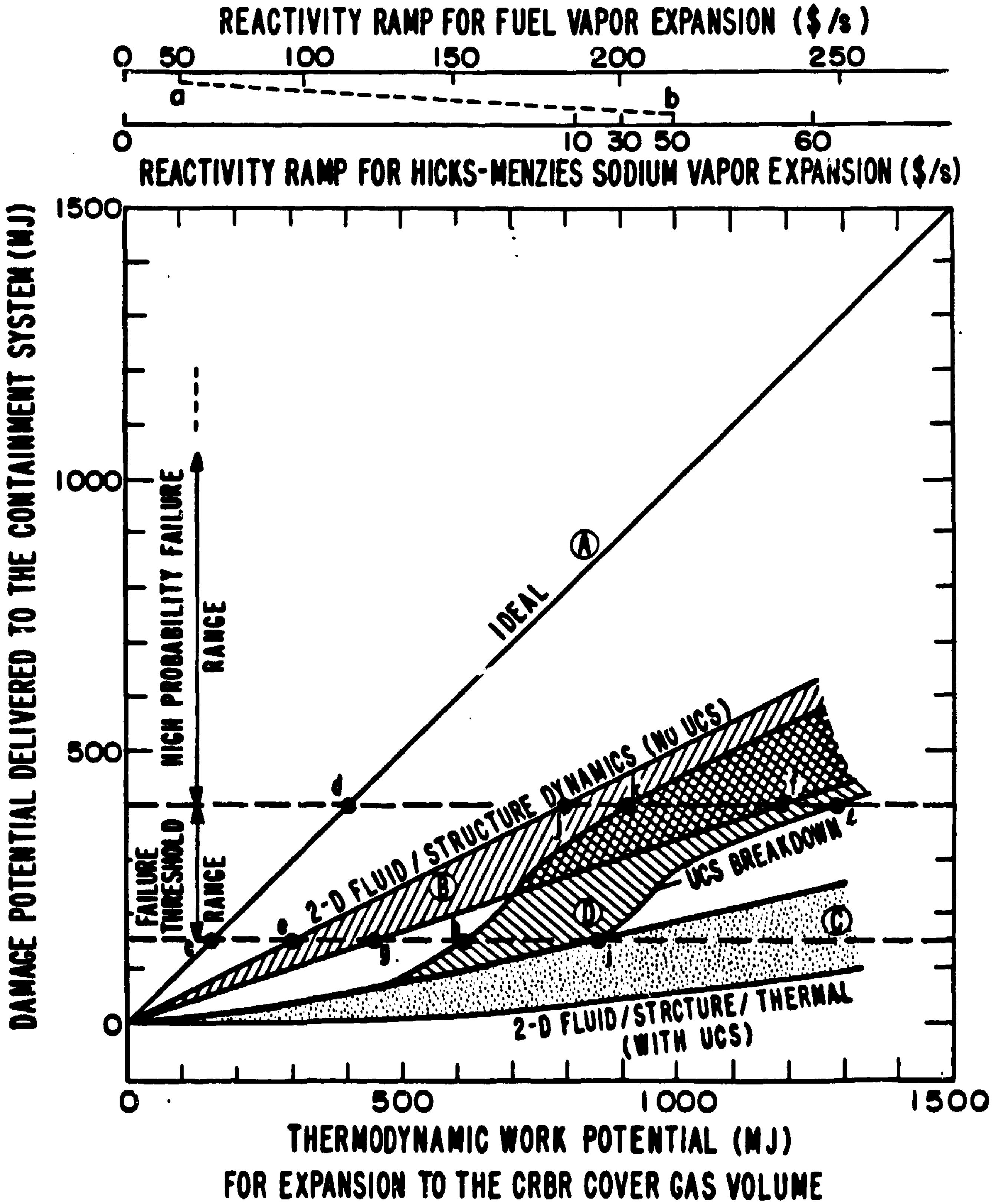

Fig. 1. Work potential to damage potential conversion diagram for CRBR.

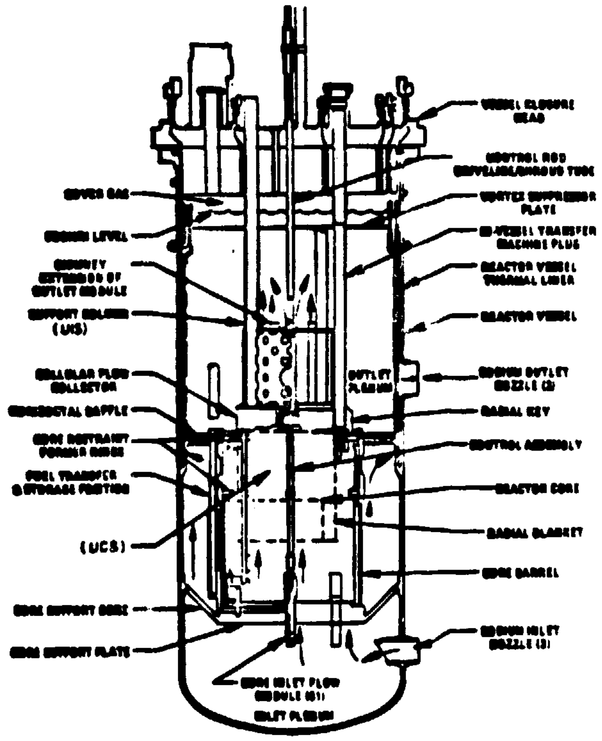

Fig. 2. CRBR schematic [17].

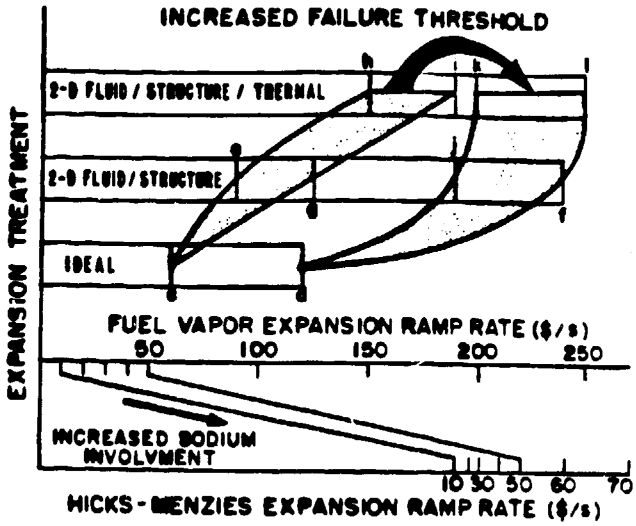

Fig. 3. Summary of CRBR tolerance for energetic accidents.

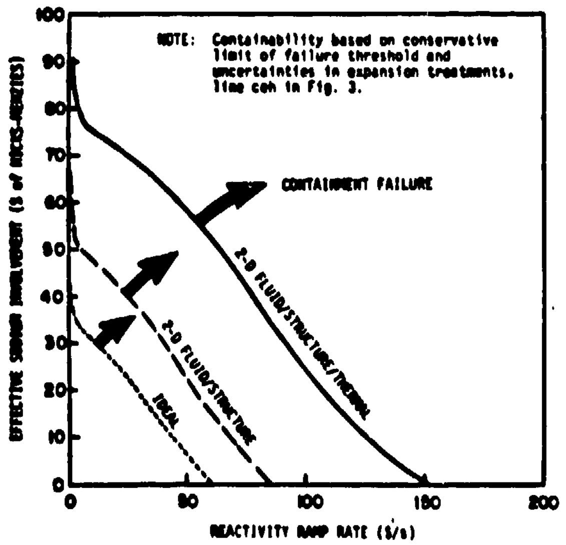

Fig. 4. Limits of effective sodium involvement for different accident severities and expansion treatments.

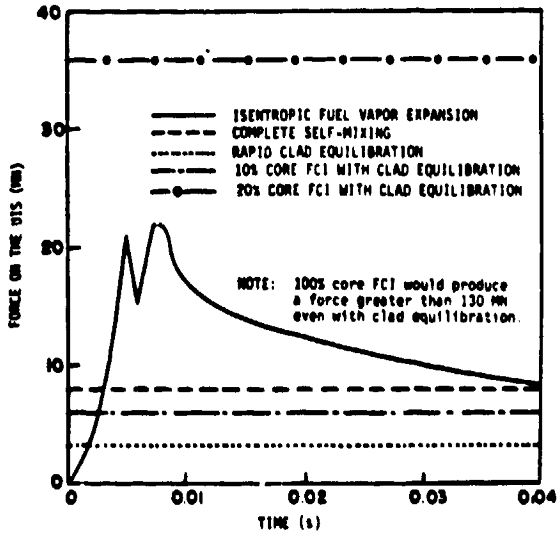

Fig. 5. Effects of heat transfer on the force applied to the UCS in the early part of a CRBR expansion (initial average fuel temperature is 4800 K).